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SHEAR-WAVE ANISOTROPY IN THE PARKFIELD VARIAN WELL VSP

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ABSTRACT

A vertical seismic profile (VSP) survey was run to 1334 m depth in the instrumented Varian well, 1.4 km from the San Andreas fault trace at Parkfield, California, to test the sensor string shortly after its permanent installation. The cable subsequently failed near the 1000 m level, so the test survey represents the deepest data acquired in the study. A shear-wave vibrator source was used at three ofsets and two orthogonal orientations, and the data have been processed for *P*- and *S*-wave velocities and for *S*-wave velocity anisotropy. Velocities are well-determined (3.3 and 1.9 km/sec, respectively, at the deeper levels), and the *S* waves are seen clearly to be split by anisotropy below about 400 m. Some 8 per cent velocity difference is apparent between polarizations parallel to and perpendicular to the San Andreas fault (faster and slower, respectively), and the difference seems to decrease with distance from the fault, suggesting that the cause may be the fabric of the fault zone. Repeated surveys at the 1000 m depth are being conducted as part of the Parkfield monitoring program.

INTRODUCTION

The method of vertical seismic profiling (VSP) has been applied in many different types of geophysical investigations (Hardage, 1985; Oristaglio, 1985). The VSP method, when used employing variably polarized shear-wave sources and three-component receivers, yields information on the anisotropic nature of the earth's elasticity. In particular, this type of VSP survey has been used extensively in quantitative studies of shear-wave velocity anisotropy. Robertson and Corrigan (1983) recorded signals from orthogonal orientations of a shear-wave vibrator to measure velocity anisotropy in shale, while Majer *et al.* (1988) and Daley *et al.* (1988a) used similar methods in studies of geothermal reservoir rocks.

Although earthquake studies have previously indicated the presence of shear-wave anisotropy (Crampin and Booth, 1985; Peacock *et al.*, 1988), the VSP method has not generally been applied to the investigation of seismically active fault zones. An exception is the Cajon Pass deep drillhole in southern California, emplaced to investigate basement rocks near the southern San Andreas fault. The Cajon Pass project included VSP studies to identify stress-induced anisotropy (Daley *et al.*, 1988b; Li *et al.*, 1988; Rector, 1988).

The research reported here was motivated by the potential use of stress-induced shear-wave anisotropy as an indicator of accumulated stress on a seismogenic fault segment. The VSP work was made possible by the availability of the 1.5 km Varian well 1.4 km from the San Andreas fault near Parkfield, California. The Parkfield segment of the San Andreas fault is the location of an intensive and multi-faceted experimental study of earthquake prediction methodology (Bakun and Lindh, 1985) because of regularly recurring magnitude 6 earthquakes there (McEvilly *et al.*, 1967; Bakun and McEvilly, 1981; Bakun and McEvilly, 1984). Seismic reflection profiles in the area were analyzed by McBride and Brown (1986) and Louie *et al.* (1988). In this article we use the shear-wave VSP method to show that a polarization-dependent shear-wave velocity is seen near the borehole, and we argue that this anisotropy is most likely due to effects of the nearby San Andreas fault, although the exact mechanism cannot be determined with this limited data set.

The Experiment

The Parkfield area has been instrumented densely with a variety of seismic and deformation detectors as part of the earthquake prediction experiment there (Bakun and Lindh, 1985). Two high-sensitivity, high-frequency downhole seismographic systems are employed in the study. A 10-station, three-component, digitally telemetered (500 samples per sec per component), borehole-emplaced (200 to 300 m), High-Resolution Seismic Network (HRSN) monitors microearthquake occurrence to $M_L \sim -0.5$ and also serves as the receiving array for the controlled-source S-wave vibrator search for evidence of precursory temporal changes in anisotropy, Q, and velocity throughout the nucleation zone of the expected earthquake. The area is illuminated monthly with S waves from three vibrator orientations at several source locations in this monitoring experiment.

The other element of the seismic instrumentation at Parkfield is a vertical array which has been installed in the previously drilled exploratory well 'Varian A1.' The Varian well, drilled to 1500 m depth, is located 1.4 km northeast of the San Andreas fault in the center of the HRSN (see Fig. 1). The Varian array contains a variety of seismometers: strong-motion accelerometers, conventional high-sensitivity geophones, and high-frequency acoustic emission sensors. The 42 individual sensor packages (36 are three-component units) were fabricated into a 1400 m molded cable with 120 conductor pairs. The entire string, attached to a 1.9-inch liner (for hydrological monitoring), was lowered into the 7-inch and then 5-inch casing, to 1.4 km, and then cemented in place. Unfortunately, the cable was apparently damaged in installation, failing over the first few months in an interval at 960 m

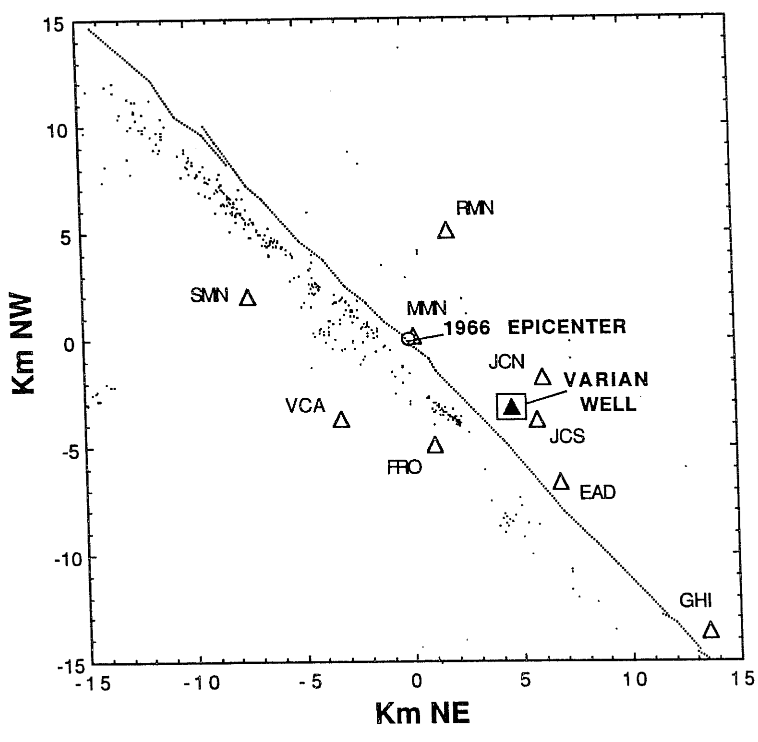


FIG. 1. Reference map for Parkfield seismic experiments showing station locations and 1987 to 1988 microearthquake activity. The origin of this map is the 1966 epicenter.

depth, resulting in nearly complete loss of signals from sensors below about 1000 m, which includes the entire acoustic emission array and much of the high-gain section. The string is currently being used in a monitoring program, both in the recording of microearthquakes and for the repeated controlled-source measurements of wave propagation properties. It also serves as a vertical strong-motion array. The array configuration as recorded during the November 1987 VSP survey is shown in Figure 2.

Shortly after installation, in a test of the cable, we recorded the upper 96 channels from a group of shear-wave vibrator source offset sites around the well (Fig. 3). Since the primary objective was a test of the array, not deep penetration, and we had not yet seen evidence of the impending cable failure, we used very few sweeps in this test, and the data exhibit only a moderate signal-to-noise ratio. Despite this limitation the results of the VSP are quite informative, and, because these are the only data recorded in the Varian well with 32 three-component sensors (the upper 96 of the total 114 seismic data channels), we present here the VSP data and a discussion of their possible implications.

Data Acquisition

The three VSP source locations are shown in Figure 3 with the two shear-wave excitation orientations assumed by the vibrator at each location. A Texas Instru-

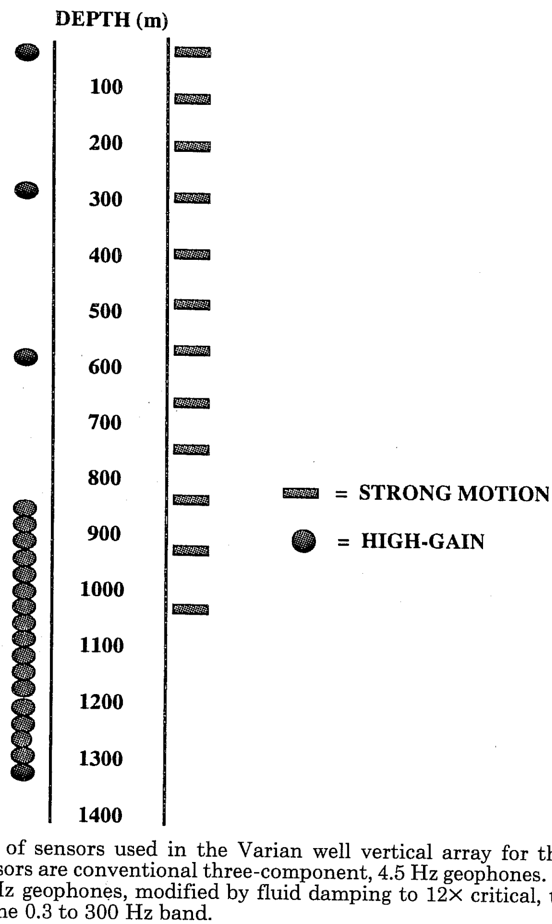


FIG. 2. Placement of sensors used in the Varian well vertical array for the November 1987 VSP survey. High-gain sensors are conventional three-component, 4.5 Hz geophones. The strong-motion units are conventional 10 Hz geophones, modified by fluid damping to 12× critical, to yield flat acceleration sensitivity (3 dB) in the 0.3 to 300 Hz band.

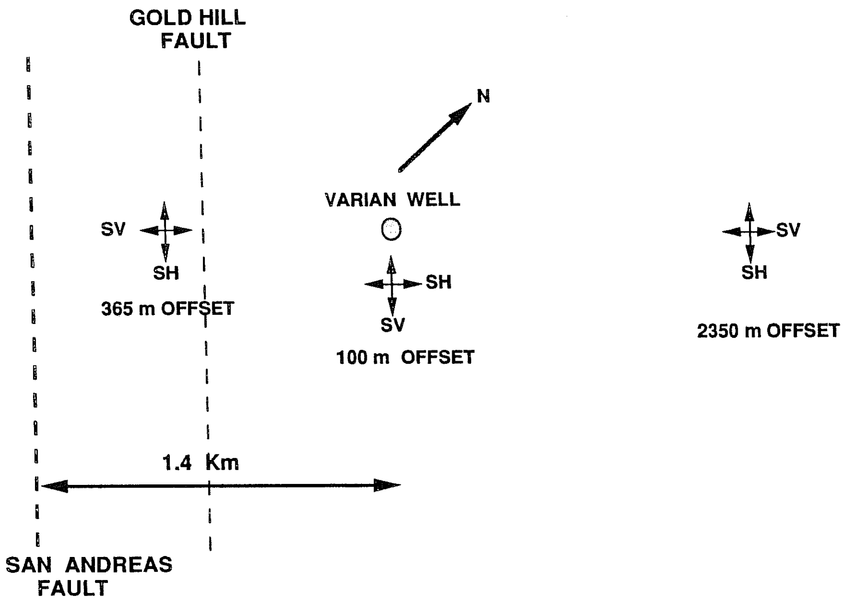


FIG. 3. Layout of the VSP survey into the Varian well, showing source polarizations and azimuths used in the survey. Offset distances are not to scale.

ments DFS-IV 48-channel recording system (courtesy of the University of California, Santa Barbara) was used, recording half of the 96 channels (three components at 32 depths) for each sweep. Sets of 5 or 6 sweeps were recorded at each source location. A 6- to 48-Hz sweep of 16 sec length and a 20 sec listening time were used. The shear-wave vibrator is from the Geophysical Measurements Facility of the University of California Lawrence Berkeley Laboratory (UCLBL).

DATA ANALYSIS

Initial processing of the records, consisting of stacking, editing, and correlation, was carried out in the Center for Computational Seismology (CCS) at UCLBL. After basic processing, travel times, average and interval velocities, and Poisson's ratio were determined using arrival times from the near-vertically propagating P and S waves from the 100 m offset data. Results are shown in Figure 4.

In addition to the P- and S-wave velocities, the controlled orientations of the shear-wave source provides a direct measurement of the more subtle shear-wave velocity anisotropy expected near the San Andreas fault (e.g., Crampin 1985). We have previously experimented with the shear-wave VSP method at the Geysers geothermal field (Majer *et al.*, 1988), at the Salton Sea Drilling Project (Daley *et al.*, 1988a), and at the Cajon Pass Deep Drillhole (Daley *et al.*, 1988b), developing procedures both for the use of variable source orientations and for signal processing and data display in the study of shear-wave velocity anisotropy.

The raw three-component data are difficult to interpret because of the nonuniform orientation of the horizontal-component geophones in the borehole. To display the data in a more useful way, we perform an eigenvalue decomposition of the waveform (Daley *et al.*, 1988a) based upon the direction of the linear particle motion of the P-wave arrival, and reconstitute (or "rotate") the three-component traces in this "wavefront-based" coordinate system (Fig. 5). Figure 6 shows the rotated three-component data for both source orientations at the 364 m offset. The 2350 m offset

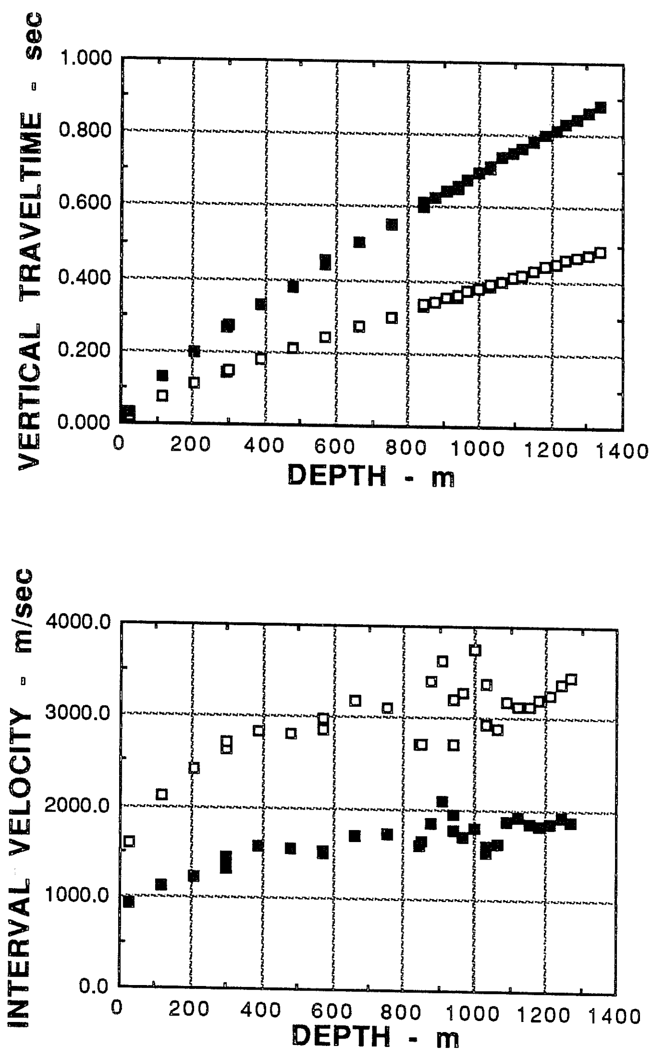


FIG. 4. Travel-times (upper figure) and interval velocities (lower figure) for nearly vertically propagating P and S waves from the 100 m source offset. S data are for the first S arrival.

data were rotated in a similar fashion. For the 100 m offset data, the ray paths are nearly vertical, precluding accurate definition of the horizontal components of the P-wave motion, so these data were rotated into a "borehole" coordinate system (Fig. 5) with the horizontal components specified by adding 90° to the azimuths obtained for the 365 m offset data (see Fig. 1). This analysis shows that the greatest change in orientation of the sensors occurs just above the depth where the cable failed, suggesting that the cable assembly was twisted and damaged during installation.

At each of the three source offsets, the vibrator was positioned twice to generate separate, orthogonally polarized horizontal forces. This exercise, an attempt at the direct measurement of S-wave velocity anisotropy, has been found useful in previous investigations of anisotropy in the shallow (0 to 2 km) crust (Daley *et al.*, 1988a, b; Leary *et al.*, 1988; Majer *et al.*, 1988). In our conventional VSP processing for anisotropy in shear-wave propagation, we define arbitrarily and independently the

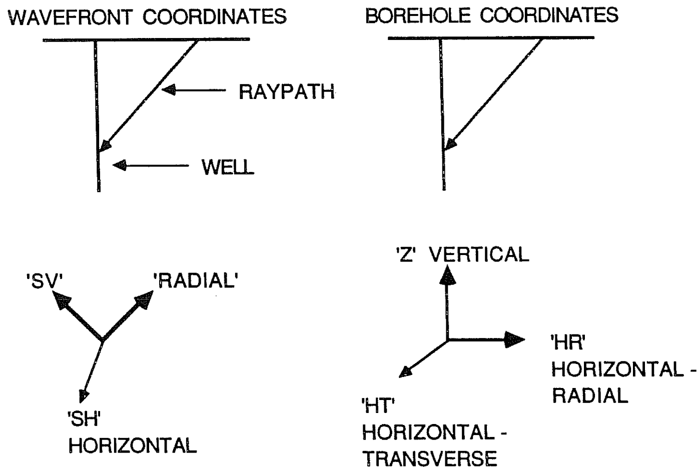


FIG. 5. Coordinate systems used in analysis of the three-component VSP data. The wavefront coordinates are based on an eigenvalue decomposition of the P-wave arrival which maximizes the P-wave energy on the radial component. The borehole coordinate system maintains the vertical component as recorded, while aligning the horizontal components parallel and perpendicular to the P-wave arrival.

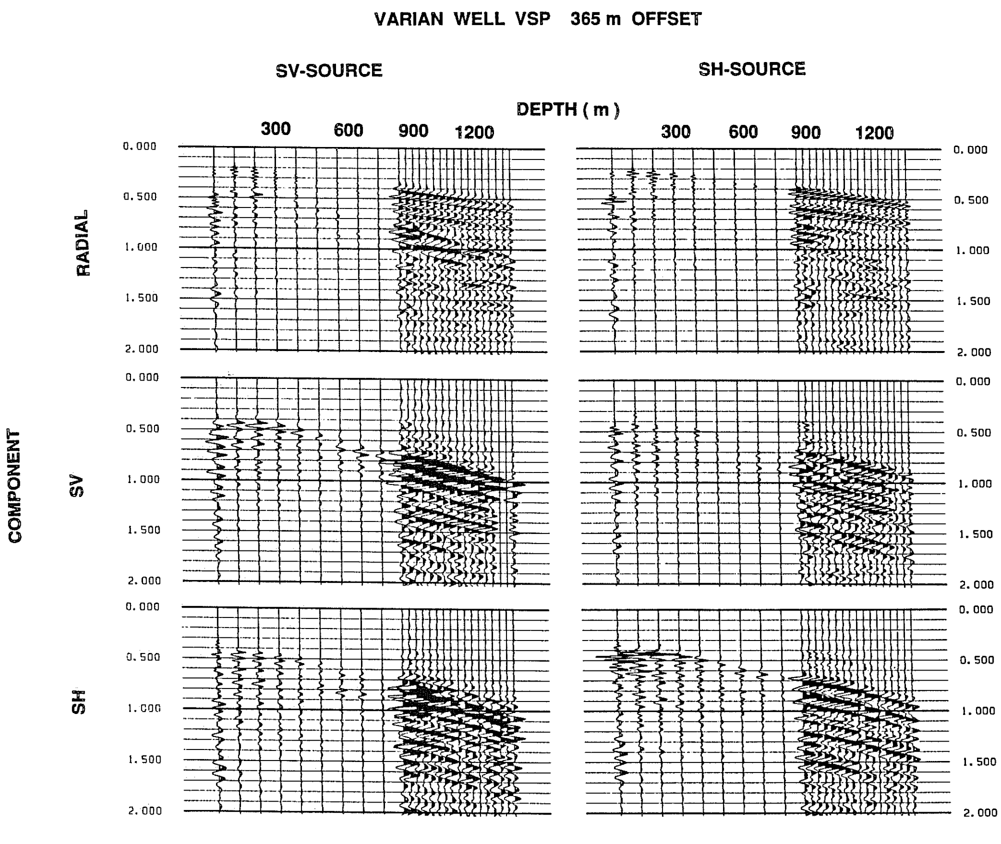


FIG. 6. VSP data for both polarizations of the source at the 365 m offset displayed in the wavefront coordinate system (see Fig. 5). All traces are plotted at true relative amplitude. The P-wave energy is well confined to the radial component for both sources. The SV source produces maximum energy on the SV component and the SH source puts maximum energy on the SH component. The lower signal levels of the accelerometers (overdamped phones above 850 m) are apparent.

two horizontal force orientations at the surface and the two orthogonal polarizations of the 'rotated' data. These coordinate directions are labeled 'SH' (for the source, SH indicates the horizontal force oriented transverse to a line from the well to the vibrator; and for particle motion, SH indicates a horizontal direction orthogonal to the P wave) and 'SV' (the horizontal source force oriented radially towards the well; and particle motion orthogonal to P and SH in a vertical plane). The two S-wave coordinate directions thus lie in a plane normal to the P wave as defined by eigenvector decomposition of the three-component P-wave data. For an isotropic, horizontally layered subsurface, this convention would define the standard P, SV, and SH waves, respectively. This convention of particle motion (P, SV, and SH) is illustrated in Figure 7, which presents the three-component data projected onto the faces of a cube with edges having the eigenvectors from the P-wave decomposition. We compare traveltimes at various depths of the SV arrival for the SV source and the SH arrival for the SH source, searching for evidence of velocity anisotropy.

Inspection of the rotated data from the 365 m offset shows a clear difference in travel time between the SV and SH components (Fig. 8a). The possibility of the variation being due to a slight difference in source position is eliminated by the identical P-wave travel times for the two sources (Fig. 8b) and by the absence of the S-wave time difference at shallow depths. In practice, the vibrator baseplate is repositioned as closely as possible onto the impression from the previous orthogonal alignment, and the two baseplate center points should not differ more than 20 to 30 cm. The travel-time difference as a function of depth (Fig. 9) indicates anisotropic material beginning around 400 m and producing a maximum travel-time difference of about 8 per cent. A change in velocity gradient is seen at that depth in Figure 4. The faster polarization, SH, has particle motion nearly parallel to the San Andreas fault (see Fig. 3). Similar analysis of the 2350 m offset data (Fig. 10) also shows a

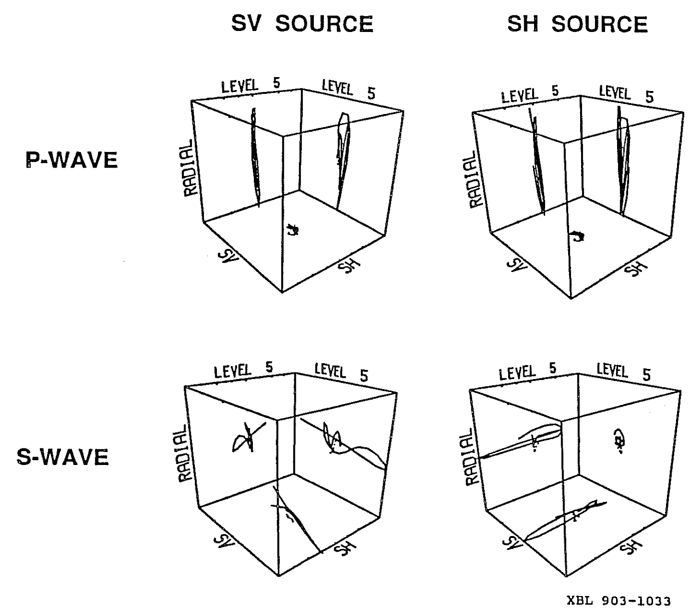
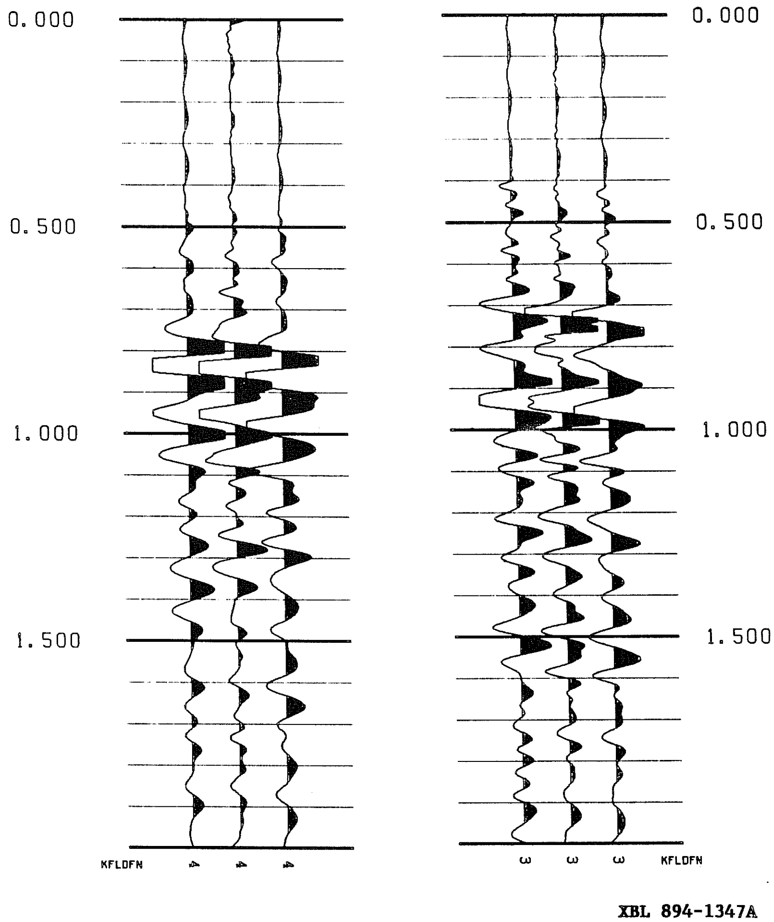


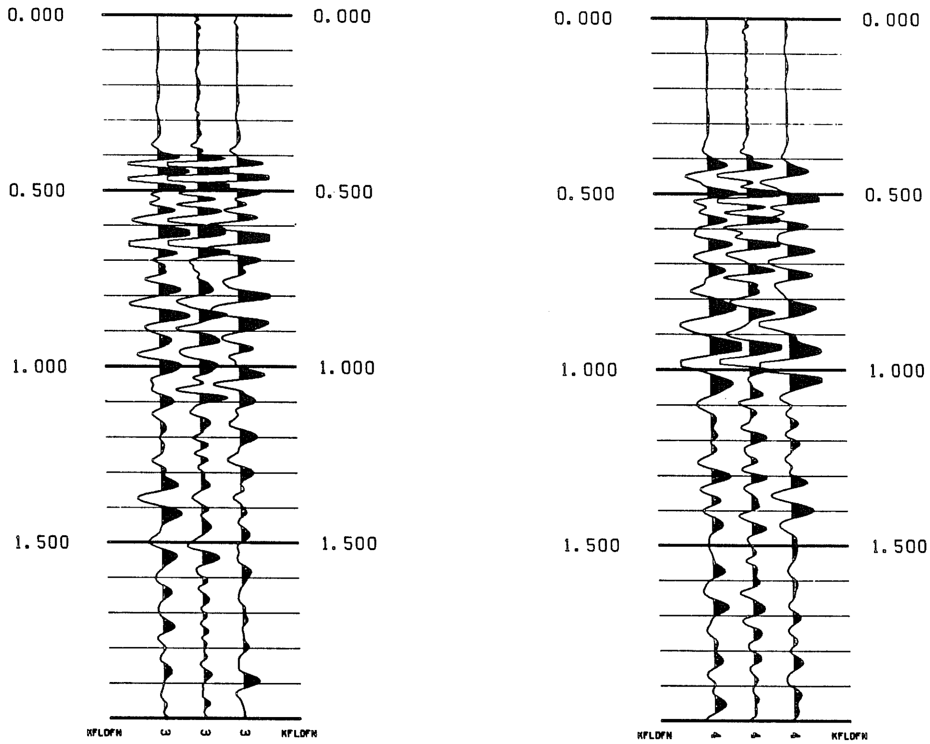
FIG. 7. Particle-motion cube presentation of the rotated data. The motion is projected onto the backside faces of the cube using the wavefront coordinate system. These data were recorded at 297 m depth for both source polarizations. Note the clearly-defined polarizations of the recorded P and S waves, and the orthogonal polarizations of the two S wave arrivals. These data are recorded within the zone of isotropic wave propagation. Each plot shows a time window of approximately 100 msec.



(a)

FIG. 8. (a) Data from the SV component for the SV source (*left*) and the SH component for the SH source (*right*). These SV and SH first arrivals show clear difference in travel-times for two orthogonal polarizations propagating between the same source and receiver points. The three depths plotted are 905, 934, and 966 m. (b) P-wave first arrivals from the SH source (*left*) and SV source (*right*) which produced the data in Figure 8a, to show that the sources were positioned at the same site (i.e., the P-wave travel times are the same). Frequency difference in the P waveforms is due to the shear vibrator P-wave generation characteristics (i.e., radiation off the side of the baseplate, normal to its motion, is higher frequency than that generated in the in-line direction). Data are from the radial component at the same depths as the data in 8a.

difference in travel time between SV and SH, but the variation with depth is not seen. At this offset the S-wave arrivals are propagating upwards in the well above 850 m, indicating relatively deep turning points, so that even the shallow arrivals appear to penetrate the anisotropic material. The S-wave velocity gradient in Figure 4 would have even the shallowest arrival (surface geophone) at 2340 m offset propagating below the gradient change at 400 m depth, and so most of the ray paths at this offset represent largely horizontal propagation, whereas the short offsets yield near-vertical ray paths. At 2350 m offset, the source and particle motion orientations roughly parallel to the San Andreas fault (SH-SH) again yield the faster S-wave arrival, though the travel-time difference is only 2 to 3 per cent. This apparent decrease in the degree of anisotropy away from the fault zone is



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(b)

FIG. 8. *(Continued)*

suggestive of a mechanism closely related to the San Andreas fault zone, and we are tempted to attribute the anisotropy to fault-zone processes. However, it must be realized that secondary phenomena, such as the complex geological structure near the fault zone at this site, must also be considered as possible causes.

DISCUSSION

In the ideal case of transverse isotropy and sources aligned with the natural axis of symmetry, the *SV* and *SH* data sets will define the anisotropic material properties (Robertson and Corrigan, 1983; Majer *et al.*, 1988). Most field data, however, indicate more complicated material properties than transverse isotropy (Daley *et al.*, 1988a, 1988b; Shearer, 1988). The Varian VSP data are no exception. In the simple case of transverse isotropy with a spatially constant axis of symmetry, two linearly polarized 'quasi' *S* arrivals, denoted qS1 and qS2, are produced with differing velocities. These arrivals will separate in time as the propagating wave field is received by the sensors positioned down the borehole. Particle motions should define the two separating waves. If the travel-time difference between the waves is large enough (one-half wave period or more), the particle motion of the mixed arrival will show two orthogonal linearly polarized motions, with the orientations of the polarizations controlled by the symmetry axis of the anisotropy.

Particle motions observed in the Varian well VSP do not support a simple

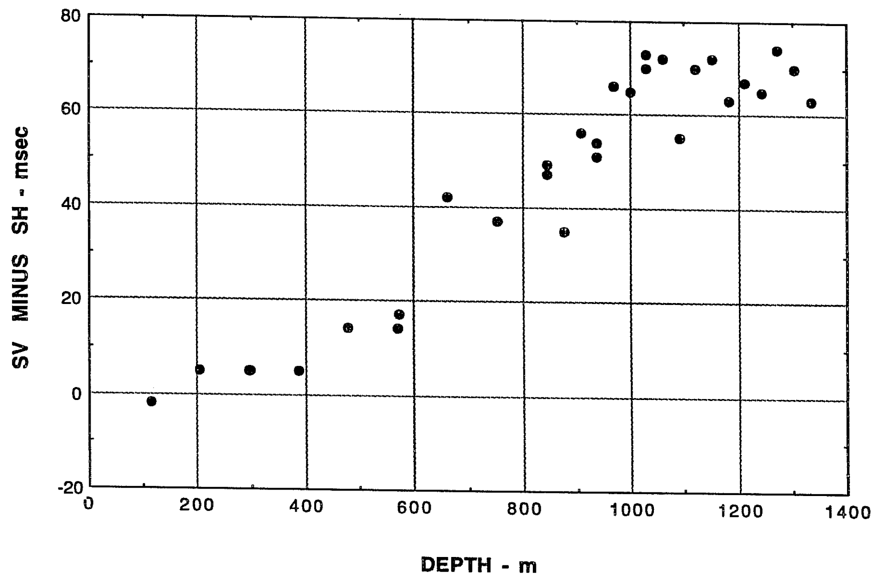

FIG. 9. Travel-time difference between SV and SH polarizations as a function of depth. The sources were at the 365 m offset. Times were picked from the SV and SH components shown in Figure 8a. Isotropic propagation will have zero travel time difference as is seen above 400 m. Below 400 m, the travel-time difference increases, implying anisotropic propagation. Times are SV minus SH.

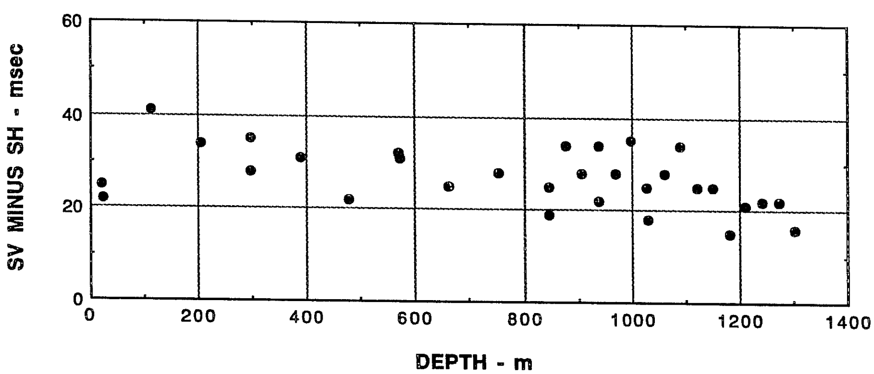

FIG. 10. Anisotropy shown by the differential travel-times of SV and SH for the 2350 m offset.

transverse isotropy model. Particle motions (see Fig. 11) show the faster SH wave developing an elliptical polarization at deeper levels, indicating a possible change in orientation of the axis of symmetry. The SV-wave polarization is elliptical at intermediate depths, possibly indicating localized zones of variation in anisotropy. The relatively low signal-to-noise ratio obtained from only six vibrator sweeps limits the quality of this particle motion analysis. However, the data suggest a medium somewhat more complex than simple uniform transverse isotropy with a horizontal axis of symmetry.

Geological studies of Sims (1990) in the area place the Varian well on the west limb of the narrow, thrust-fault bounded Parkfield syncline which parallels the San Andreas fault. The well penetrates the Miocene Etchegoin, Monterey and Temblor formations, bottoming in rocks of the Franciscan assemblage. The Etchegoin/ Monterey contact may control the velocity gradient change at 400 to 600 m depth,

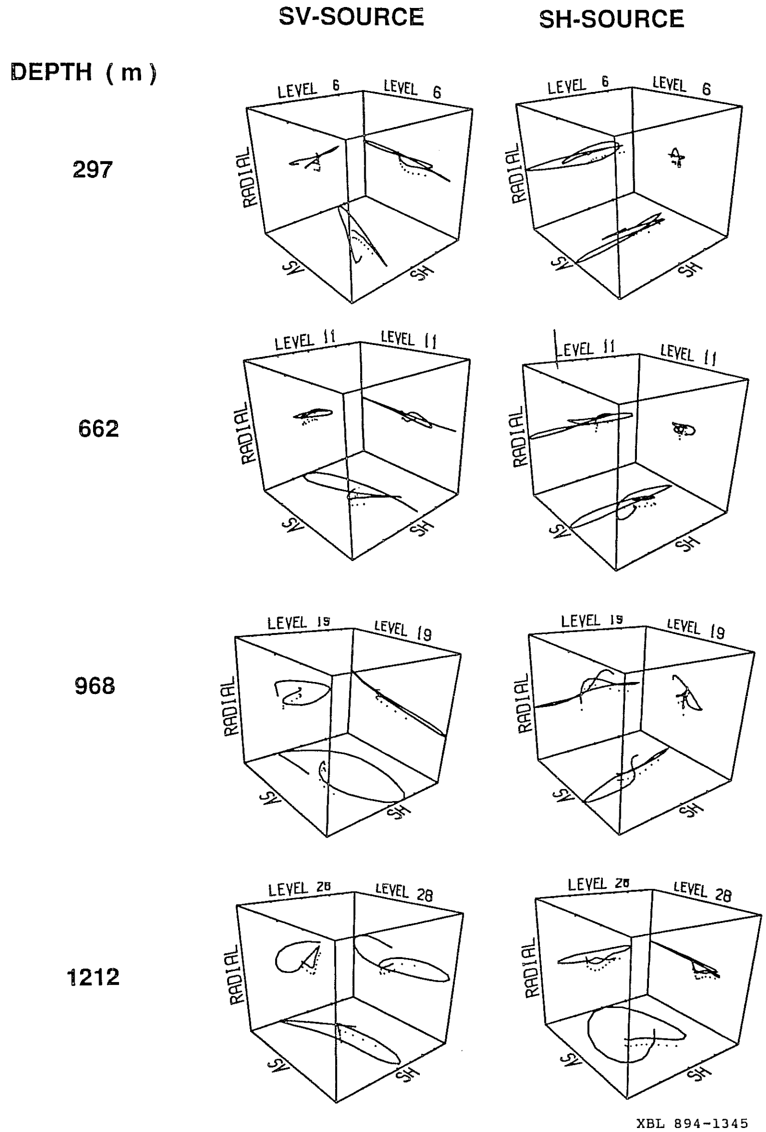

FIG. 11. Particle-motion cubes for the first S arrival at two source polarizations, 365 m offset, for several depths (see Fig. 7 description). Note the development of elliptical polarizations at some depths (see text). The arrivals are nearly orthogonal at all depths except 1212 m where the SH-source arrival is nearly circularly polarized.

and the anisotropy appears be developed within the Monterey formation. Dips are about 45° to the east at the well. The 365 m offset vibrator source position, to the west of the well, is just west of the Gold Hill fault, a steeply west-dipping reverse fault which bounds the Parkfield syncline on its west limb. Ray paths showing the anisotropy are thus propagating obliquely across the bedding of the Monterey, and this may be a source of the observed phemomenon. However, ray paths from the source offset 2350 m to the east appear to have similar length and geometries as ray paths from the 365 m offset for those ray segments within the Monterey formation (much of the added path length is confined to the Etchegoin). Therefore, the difference in shear-wave splitting between the 2350 m and 365 m offsets suggests that proximity to the San Andreas fault zone and sampling of its 'fabric' (which can include the near-vertical Gold Hill fault) may be the controlling factor in the observed shear-wave anisotropy.

Transverse isotropy with a horizontal axis of symmetry normal to the San Andreas fault zone, thus does provide a first-order model for propagation of shear waves near the San Andreas fault. Assuming two intrinsic polarizations for the 'split' quasi shear-waves, the model predicts faster propagation for waves polarized as SH (parallel to the fault) and slower propagation for waves polarized as SV (perpendicular to the fault). A simple model of thin vertical layers or cracks, aligned parallel to the fault, could give the result. The degree of anisotropy appears to increase toward the fault zone, implying that the fault is controlling the phemomenon. Assuming fault-controlled velocity anisotropy, our data suggest a physical model involving a zone of vertically oriented shear fabric near the fault, probably developed from the long-term continuing slip. The extent of this shearing would decrease away from the fault, and the fabric orientation would be parallel to the fault. While this simple model cannot explain all of the observed particle motion phenomena in the wavefield, it does provide an initial hypothesis which can be tested in continuing experiments in the Parkfield area. To this end, a more complete multi-azimuth, multi-offset VSP survey has been conducted to the presently accessible depth of about 1 km, which will sample the upper half of the Monterey formation, and it may provide a more definitive interpretation of the nature and mechanism for the anisotropy.

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